

**CERRO XALAPAXCO: AN UNUSUAL TUFF CONE WITH MULTIPLE  
EXPLOSION CRATERS, IN CENTRAL MEXICO (PUEBLA)**

by

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submitted to

Journal of Volcanology and Geothermal Research

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## ABSTRACT

The **Xalapaxco** tuff cone is located on the northeast flank of La Malinche stratovolcano in central Mexico. An unusually large number (10) of explosion craters, concentrated on the central and on the uphill side of the cone, expose alternating beds of stratified surge deposits and massive fall deposits. The morphology of the cone and the characteristics of its deposits point to the involvement of significant quantities of groundwater during its eruption. The phreatomagmatic eruptions which led to the cone's formation pierced an alluvial fan, whose source is a glacially carved canyon near the summit of La Malinche volcano. The large canyon was cut during repeated glacial episodes, the last of which ended ca. 8,500 years ago. The present alluvial fan mostly consists of reworked glacio-fluvial andesite/dacite material from La Malinche. Rising magma encountered substantial amounts of groundwater within the limestone basement and in overlying intercalated pyroclastic and glacio-fluvial deposits of the alluvial fan. Short-lived phreatomagmatic eruptions produced surge and airfall deposits. Xenoliths found in the cone beds are composed of dacite and andesite clasts, limestone, chert, and rare ignimbrite fragments. No juvenile material could be unequivocally identified, but is represented most probably by porphyritic dacite similar in texture and composition to La Malinche lavas. The multiple craters were formed as a response to changes in water and magma supply during the short-lived eruption. Hence, the locations where ideal magma/water ratios existed to fuel phreatomagmatic explosions shifted in time and space. Analysis of diameter/depth ratios of the craters indicates that the activity shifted from the center of the cone to its periphery in the west. Due to the configuration of the hydrographic environment, more groundwater flowing from La Malinche was available from the fan on the uphill side than below the cone at later stages of the eruption. The apparently anomalous position of the tuff cone on the slopes of a stratovolcano in a presently dry environment can be explained by more humid climatic conditions prevailing at the time of eruption.

## introduction

The Xalapaxco tuff cone is located in the central part of the Trans-Mexican Volcanic Belt (TMVB), 35 km northeast of the city of Puebla, on the southwestern edge of the Srd6n-Oriental Basin (Figure 1). It is situated near the base of the northeast flank of La Malinche, a Tertiary-Quaternary andesitic stratovolcano that reaches 4503 m in altitude and is believed to be extinct (Heine, 1975) (Figure 2).

About a dozen other phreatomagmatic explosion craters occur in the Srd6n-Oriental intermontane basin, several of which bear either the name Xalapaxco or Axalapaxco depending on whether they contain a lake in their crater. *Xalapaxco* is a word in Nahuatl (the language spoken by the Aztecs) meaning vessel or container made of sand. An *Axalapaxco* is a vessel made of sand that contains water. Therefore the term *Xalapaxco* can be envisaged as the equivalent of a tuff cone or dry tuff ring, and *Axalapaxco* as a maar.

Ordoñez (1905, 1906) was the first to study tuff rings in the Srd6n-Oriental intermontane basin, and to recognize that they were phreatomagmatic in origin, although he did not include Xalapaxco tuff cone, described here, in his studies. Von Erfffa et al. (1977) were the first to mention Xalapaxco and recognize its probable young age by its morphology. Xalapaxco is in many respects a typical tuff cone. But the unusually large number of explosion craters which indent its surface attracted our attention. A survey of the literature revealed that no other place in the world has a similar tuff cone with so many craters. It is the purpose of this paper to provide the first description of Xalapaxco and speculate about the possible origin of its multiple craters.

## General Setting

We first noticed Xalapaxco while analyzing Landsat Thematic Mapper satellite images of the Srd6n-Oriental Basin. This closed intermontane basin has an area of about 15,000 km<sup>2</sup> and an altitude of approximately 2300 m a.s.l. It represents the easternmost part of the Mexican Altiplano and is surrounded by Miocene to Quaternary stratovolcanoes and calderas, which are mainly andesitic to dacitic in composition. During the Quaternary the basin of Srd6n-Oriental and nearby

areas were affected by dramatic climatic changes. Extensive lakes occupied the interior of the basin and large glaciers covered the summits of surrounding volcanoes including La Malinche. Remnants of these lakes still exist in the lowest parts of the basin (Ohgemach and Straka, 1983).

Within the flat basin are numerous tuff rings and cinder cones, as well as large monogenetic rhyolite domes (Siebe, 1986; Siebe and Verma, 1988). Formation of tuff rings within a depression such as the Serdán-Oriental is not surprising since most other documented phreatomagmatic craters are found in topographically low positions at the bottom of valleys; in basins associated with existing or previous lakes (White, 1990, 1991) swamps, and marshes; or near the seashore (Ollier, 1974; Lorenz, 1973; Wohletz, 1990). In topographically low areas rising magma will encounter most likely enough ground- or surface water to interact with. Tuff cones generally form in wetter environments, typically where shallow water is present at the surface (Wohletz and Sheridan, 1983). Xalapaxco is the only tuff cone in the area, all other phreatomagmatic craters are tuff rings. Formation of a tuff cone at relatively high elevations, along the slope of Malinche volcano, seemed peculiar, as no obvious water body was apparent. We suspected that the Xalapaxco tuff cone formed as the result of the interaction of magma with abundant water in an anomalous hydrologic situation.

In addition to volcanic edifices and eruptive products in the Serdán-Oriental Basin are mountain ridges of Upper Cretaceous limestone which form the exposed basement of the region (Yañez García, 1980). The limestones are thinly bedded and contain lenses and nodules of dark chert. They were tightly folded and faulted prior to onset of the volcanic activity in the area.

Examination of the Landsat Thematic Mapper satellite image covering a 60 x 60 km area centered on La Malinche volcano (Figure 3) revealed the presence of a drainage anomaly around the Xalapaxco tuff cone. The cone is situated in the middle of a large alluvial fan, which heads a major incised canyon (Barranca Axaltzintle). This is the largest erosional feature which drains the upper summit area of the volcano. For the most part, the drainages formed on the slopes of La Malinche are locally subparallel and dense, and form a radial pattern (Figure 4). These characteristics are consistent with the underlying fine-grained and uniform pyroclastic deposits

exposed in barranca walls. The area around Xalapaxco is relatively free of drainages; a fairly blank triangular area is shown on the drainage interpretation, corresponding to the area of the fan. Most of Xalapasco's explosion craters are clustered on the side of the cone that faces the NE slopes of La Malinche.

### **Morphology of Xalapaxco and its Craters**

The Xalapaxco tuff cone is an asymmetric structure with a height of 150 m and basal diameter of 1900 m, yielding a height/base ratio of about 1:12, which is within the typical values for other tuff cones. The surface of the cone is actively farmed, as a modest soil has developed from covering ash deposits. The unusual feature of this cone is the large number of explosion craters which indent its summit and flanks. The 10 craters range in diameter from 436 m to 111 m (Figure 5), and in depth from 98 m to 25 m (Table 1). Their diameter/depth ratios vary from 7.4 to 2.9, the smaller numbers represent the deeper, less filled-in craters. Of the two pairs of superposed craters producing a "figure 8" configuration (1 and 2; 4 and 5), we infer that the crater with the smaller diameter/depth is younger, and may have ejected material that filled the crater with the larger ratio (Figure 6). The deepest explosion crater is almost 100 m deep, although like the other craters, it is partially filled with slump debris. The 10 explosion craters on Xalapaxco are distributed unevenly; most of them are located on the uphill side of the cone, facing La Malinche (Figures 2 and 5).

### **Stratigraphy and composition of clasts**

Vegetation is extensive in all the craters, obscuring the walls and hiding the stratigraphy. Only in crater 1 was it possible to measure a nearly continuous, 52 m thick section. In the rest of the craters, only a few to ten meters of section are exposed. Bedding directions are inward-dipping on the inside of the craters, and outward-dipping on the flanks of the cone. Walls within nested craters show overlapping inward and outward dipping strata, depending on which crater was active and the exact cross-cutting relationships. Typical dips are between 5 and 15 degrees for the

outward dipping material, and 24 degrees for the inward dipping beds. The craters are generally filled, at least in part, by reworked tuff from slumping of the inward-dipping beds, widening the original craters and removing most of the inward-dipping material (White, 1990).

In every outcrop examined, the material was the same. Predominant are fall deposits and surge deposits. This is illustrated by the 52 m section measured in the NW wall of crater 1. The bottom 15 m consists of sorted, 5 cm thick planar beds of fine material ranging from sand to silt to clay sized particles. Neither grading nor large xenoliths or clasts are evident. The next 13 m are interlayered lithic-rich and lithic-poor planar beds. Representative grain size analyses are shown in Figure 7. The lithic-rich beds are 5-10 cm thick, clay-poor, and are well indurated. They are well sorted, with clasts up to 12 cm. impact sags occur beneath larger clasts. Clasts are gray and pink dacite and andesite, with fresh-looking plagioclase and biotite phenocrysts, and reddish, partly oxidized hornblende crystals; rare clasts of dark chert and gray limestone also occur. The lithic-poor beds are finely laminated, buff colored, with sand to silt sized clasts. Clasts are of similar composition to that seen lower down. The upper 24 m are made up dominantly of lithic-poor planar-bedded layers, 5-10 cm thick. They are semi-indurated, clay-rich, and not graded. Occasional lithic-rich horizons are well sorted, and up to 15 cm thick. Clasts range up to 15 cm; compositionally they are 95% andesites and dacites, with rare clasts of limestone, chert, and violet ignimbrite. Planar bedding is the most common seen in all exposures, typical for low energy surges (Wohletz and Sheridan, 1983); impact sags with angular blocks are also seen (Figure 8).

Other exposures show some variation on this measured section: in places, 10-20% of the layers are composed of 2-6 cm thick gravel-cobble layers composed of andesite and rare chert. Also seen are occasional layers showing reverse grading. Rare scour channels 30 cm across are exposed in some of the vents. Unlayered, unsorted layers are also seen, with subangular to subrounded clasts up to 1 m in diameter.

The most frequent type of clasts (ca. 80% of the entire volume) consists of a dense dacite which is gray in color with clearly visible phenocrysts of hornblende, plagioclase, and biotite. Where weathered, this dacite is reddish-brown in color. Microscopically this rock is characterized

by strongly zoned, partially resorbed labradorite phenocrysts (up to 3 mm in length, containing fluid inclusions, apatite needles, and magnetite grains), pleochroic oxy-hornblende. (up to 3 mm length, often isomorphic with opacite rims) and brown biotite phenocrysts (up to 2 mm, pleochroic) which are embedded in a hyalopilitic groundmass containing mostly second generation feldspars, magnetite grains, and glass (samples 9102 and 9104 in Tables 2 and 3). This rock is identical to the boulders and gravel that form the bulk of the glacio-fluvial fan surrounding the cone and which has its origin at La Malinche.

The second most frequent type of clasts (ca. 10% by volume) consists of a limestone which is light gray in color and contains abundant chert nodules. The chert nodules are either dark flint or white novaculite; they are probably diagenetic in origin and mostly replacive. Since many of the chert nodules (especially the black flint) occur as isolated angular fragments up to 5 cm in size within the tuff layers of Xalapaxco, we first interpreted them to be juvenile volcanic glass. However, inspection under the microscope and chemical analyses revealed their true identity. The chert consists mostly of an aggregate of equidimensional grains of microcrystalline quartz with abundant water inclusions (sample 9103 in Table 2). The limestone and chert fragments are identical to those outcropping in nearby areas and forming elongated ridges within the Serdán-Oriental Basin and belong to either the Cretaceous Tamaulipas Formation or the Orizaba Formation (Yañez García, 1980; von Erffa et al., 1977).

In addition to the gray dacite and Cretaceous cherty limestone, other clasts, mostly volcanic in origin, such as white chalcedony occur. They are absolutely subordinate and negligible by volume. Noteworthy to mention are also a few clasts of violet color that microscopically seem to have the flow structure of an extrusive rhyolite. Under the microscope, these clasts turned out to be fragments of densely welded ash flow tuffs (sample 9101 in Tables 2 and 3). They showed typical alignment of glass shards due to compression during compaction. The compressed shards are molded against phenocrysts of plagioclase and biotite which may show local resorption embayments. They are largely glassy but the margins show incipient devitrification, the products of which are too fine to be resolved by the microscope. Extremely flattened pumice fragments

embedded in shard material also occur. The devitrification of the minute pumice lenses has destroyed their original fibrous structure.

#### Scanning Electron Microscopy (SEM) observations

Since no definitive juvenile material could be identified within the coarser deposits, samples taken from surge deposits were examined with the scanning electron microscope (SEM). Samples were sieved and the 1  $\phi$  fraction isolated and cleaned using the method described in Komorowski (1991). Inspection under the binocular microscope revealed that most grains represent the gray La Malinche dacite that occurs abundantly in the alluvial fan. In addition, as we found microscopically, chert and limestone were the second most frequent constituents. A variety of particles were mounted and analyzed by SEM. Identification of grains was made with an Energy Dispersive Spectrum X-ray analysis system (EDS). A few grains of volcanic glass were identified. Whether or not these are juvenile is difficult to ascertain. All grains are very rounded with pitted surface textures displaying a high degree of abrasion and edge modification (Figure 9) not typical of particles from pyroclastic surge deposits as described in Heiken and Wohletz (1985). This is compatible with a strong degree of postfragmentation particle-particle interaction during transportation prior to final deposition. Apparently subsequent explosions reworked and redeposited already existing surge deposits.

#### Composition and origin of the alluvial fan

We inspected the prominent alluvial fan on which Xalapaxco is built. At a distance of 3 km downslope of the tuff cone are a number of small quarries which the local residents have developed as a source of sand, rounded cobbles, and gravel. Compositionally, the rocks are the same monotonous gray and reddish dacites and andesites that are so abundant in Xalapaxco's deposits and represent the bulk of its mass. The material is typically unsorted, and has clearly been deposited fluvially as outwash. Based on these observations, we conclude that the basement directly underneath the Xalapaxco cone is, at least in part, composed of reworked fluvial and



alluvial gravels and cobbles, the source of which was La Malinche. The products of this volcano are lithologically very homogeneous and monotonous.

At present, the climate in the area is semiarid. The arroyos are dry most of the year, except for the rainy season, when sheet floods can occur after heavy rainstorms. These floods normally cover only a small area of the entire fan suggesting that this type of phenomenon must have been more frequent and intense in previous geologic time to produce the fan.

Previous studies of the paleoclimate and ages of glacial events shed some light on the origin of the alluvial fan and hence the history of the tuff cone, its formation, and its age. Glaciomorphological and paleoclimatic studies at Mexican stratovolcanoes have shown that several glaciations occurred in the Late Pleistocene (White, 1951, 1962; Heine, 1975, 1988; White et al., 1990). The Late Quaternary stratigraphic succession of La Malinche has been studied by the "Mexico Project" of the German Science Foundation (Heine, 1973; 1975; 1984; 1988). In the erosional gullies starting from the upper reaches of the volcano and extending towards the basins they found exposed layers of glacial and peri-glacial deposits, paleosols, debris, fluvial gravels and sands, and interbedded lava flows, ignimbrite deposits and tephra. Dating of some of the layers was accomplished by radiocarbon dating of charcoal. Relative age dating methods included topographic position and morphological shape of moraines, rock-weathering parameters, soil properties, and lichen development. Five glacial advances have been identified during the last 40,000 years in central Mexico: maxima at 33,000-35,000 yr BP (MI), about 12,000 yr BP (MII), and 8,500-10,000 yr BP (MIJ); and lesser advances at 2,500-3,000 yr BP (MIV) and 500 yr BP (MV). These events were correlated at other volcanoes all over the entire central Mexican highland, and thus apparently do not represent local fluctuations. Maximum periods of humidity, and hence intensive fluvial and glacial erosion and strong mass movement, correspond to the glacial maxima MIII, MII, and MI. Events MIV and MV did not affect La Malinche due to its lower elevation compared to higher peaks, such as Popocatepetl, and Pico de Orizaba (Heine, 1984). We suggest that most of the large canyon, Barranca Axaltzintle, at the head of the Xalapaxco alluvial fan, was glacially formed during these more intense glacial events. The alluvial

fan at the base of the canyon represents outwash of reworked glacial material, composed dominantly of andesite and dacite clasts from La Malinche.

## Discussion

Several key questions regarding the formation of Xalapaxco have not been addressed yet. They include: 1) What is the juvenile material and what is the ratio of juvenile to non-juvenile clasts? 2) Why is Xalapaxco a positive landform and not a “hole in the ground” as other phreatomagmatic craters in the Sierra Oriental? 3) What were the prevailing hydrologic conditions at the time of eruption? 4) Why does Xalapaxco have so many craters, were they formed at the same time or did they erupt in a certain sequence? 5) What is the age of Xalapaxco? The answers to these questions are strongly interrelated and will be addressed in the following paragraphs.

Field observations, mineralogical and chemical analyses of gravel and boulders, as well as inspection of ash particles under the binocular and scanning electron microscope, all indicate that Xalapaxco is mostly phreatomagmatic in origin. Considering its general morphology, texture of the deposits, and the types of constituent material, Xalapaxco can best be defined as a tuff cone. Tuff cones are a type of hydrovolcanic explosive construct, forming a continuum from maars and tuff rings (Ollier, 1967; Fisher and Waters, 1970; Wohletz, 1986; White, 1991), to tuff cones (Lorenz et al., 1970; Heiken, 1971; Lorenz, 1971; 1973; Self and Sparks, 1978; Sheridan and Wohletz, 1983; Wohletz and Sheridan, 1983; Lorenz, 1986). They are formed during the interaction of magma or magmatic heat with an external source of water, such as a lake or groundwater (Sheridan and Wohletz, 1981). Tuff cones are distinguished by their larger height to basal diameter ratios (typically about 1:5 to 1:15) compared to tuff rings (values less than 1:25). Tuff cones are typically formed from wet surges (condensing steam media) rather than dry surges (superheated steam media) (Sheridan and Wohletz, 1983) and are constructed by multiple phreatomagmatic eruptions and explosions that can eject both juvenile and non-juvenile material, exotic blocks from the basement, and hydroclastic ash. The ash can be interpreted as fallout from milder episodes of activity, or as more violently deposited base surge materials (Fisher and Waters,

1970; Waters and Fisher, 1971; Schmincke et al., 1973; Self et al., 1980). The three principal deposit types found in tuff cones are: (1) explosion breccia; coarse-grained, chaotic pyroclastic deposits near the base of tuff cones; (2) thinly bedded deposits that include surges and have near horizontal bedding; and (3) thickly bedded deposits; showing indistinct or poorly developed bedding, often strongly indurated (Wohletz and Sheridan, 1983).

All of these types of deposits occur at Xalapaxco although (2) and (3) are by far the most abundant. Evidence for the eruptive mechanism is seen in the planar bedding, degree of induration, occasional dune structures, incut channels, etc. These all point to phreatomagmatic eruptions of low to moderate energy. A uniform eruptive style is seen; no switch of eruptive style from phreatic to strombolian, for example, is evidenced in any exposures. All surges appear to have been moderately wet, attesting, to either a short-lived eruption, or static eruption conditions. The lack of soil development or erosion anywhere in the sections also indicates a short-lived eruptive history.

From our petrologic examinations we were unable to identify juvenile material. Therefore the relative proportions of juvenile and non-juvenile material erupted from Xalapaxco could not be ascertained, but it might be similar to those reported for other tuff cones.

Because Xalapaxco is a positive construct, juvenile magma must have been present and is most probably represented by a fraction of the porphyritic gray andesite/dacite that forms the bulk mass of Xalapaxco. This means that the juvenile magma is almost identical in composition to the La Malinche porphyritic andesites/dacites that compose the alluvial fan.

Surface water was probably provided only by the stream that drains La Malinche's glacial valley. Water for phreatomagmatic eruptions must have been supplied, therefore, by subsurface sources: the fluvial gravels and/or the Cretaceous limestone. The abundance of andesite/dacite in Xalapaxco's deposits suggest that phreatomagmatic explosions took place mostly at very shallow depths, where rising porphyritic viscous magma began to spread out like a laccolith when it reached the unconsolidated less dense fluvial sequence. It appears that it is the shallow depth of the phreatomagmatic explosions, that is mostly responsible for the formation of a tuff cone

rather than a tuff ring with a deep crater as occurs elsewhere in the central part of the Serdán-Oriental basin. The relatively thin sequence of fluvial gravels covering the dense limestone basement below Xalapaxco provided enough water for phreatomagmatic activity, but this situation did not allow high pressures to exist. Therefore most explosions were rather weak and the ejected material piled up near the vents. In the center of the basin where the loose infill is much thicker, explosions took place at greater depths and were much stronger, leading to a wider dispersal of the ejecta and formation of deeper craters with smaller rims.

Interaction of the magma with water fueled the phreatomagmatic eruptions. The magma was probably continuously fed by more water from the aquifer in the gravels, than was flowing at the surface downhill from the direction of La Malinche. This is the reason, we believe, that most of the craters exploded on the uphill (water-rich) side of the cone, and are not more randomly distributed.

We assume that first the main large crater (#1) formed. At this vent most of the phreatomagmatic explosions that constructed the cone took place at shallow depth. The activity at the main crater might have ceased when the available groundwater at that place was mostly consumed. The laccolithic magma body continued spreading laterally under the cone near the contact between the limestone and the alluvial gravels. Activity resumed in the areas to the W and SW where groundwater flowing from La Malinche towards the eruption site, was sufficient to continue fueling phreatomagmatic explosions forming the peripheral craters. This means that it is unlikely that all craters erupted at the same time. Since magma and groundwater supply changed through time, the locations where the ideal magma/water ratios for fueling phreatomagmatic explosions would be encountered also changed.

The diameter/depth ratios for the different craters might shed some light on their order of appearance. Assuming that all craters initially had a similar form, craters with high diameter/depth ratios were probably the first to form, while craters with small ratios were probably the youngest in appearance. According to this hypothesis the craters would have been formed in the following order: 10, 2, 3, 4, 1, 7, 9, 8, 5, and 6. Conversely, the maximum diameter seems to be the most

appropriate parameter to determine the duration of activity at each crater, independently of the order in which the craters formed, because their depth might have diminished after cessation of activity due to later infill by material ejected by neighbouring craters. According to this assumption the craters can be catalogued in the following order (from longest to shortest duration of activity): 1, 3, 2, 10, 9, 8, 5, 7, 4, and 6. From the above considerations a general spatial and temporal trend can be observed: Craters 1, 2, and 3 at or near the main summit area of Xalapaxco were the first to appear and were active for longer periods of time, while craters 5, 6, 7, and 8 in the western and southwestern periphery facing La Malinche were formed at the end of the eruption and were active for a short time span. This shift in activity from the central summit area to the western periphery is also supported by stratigraphic relations.

Due to the absence of charcoal or other material datable by the C-14 method, we were not able to obtain any absolute geochronologic data on Xalapaxco's deposits. Stratigraphic relations indicate that the age of Xalapaxco is younger than the deposition of most material that comprises the alluvial fan, which was formed as a response to repeated glacial activity at La Malinche. Hence it is younger than the last major glaciation, which occurred about 8000 to 10000 years ago. At present, climatic conditions in the area are semiarid and it is questionable if the alluvial fan would provide enough groundwater from the high country of La Malinche to fuel phreatomagmatic explosions in case of renewed volcanic activity. For this reason we speculate that Xalapaxco formed during the vanishing stages of the last glaciation, when more groundwater was available and the hydrologic conditions were more favorable for phreatomagmatic activity.

## Conclusions

Based on our investigation, we infer that the Xalapaxco tuff cone formed when rising magma encountered sufficient volumes of ground water in the alluvial fan heading from the glacial valley on the east side of La Malinche volcano, as well as in the saturated Cretaceous limestone basement. A suggested cross-section through the cone (Figure 10) shows the lowest basement material to be folded Cretaceous limestone, as evidenced by limestone and chert clasts found as

exotic inclusions in the Xalapaxcotuff cone strata, and the nature of nearby limestone outcrops. Overlying the limestone beds are most probably a series of fluvial layers intercalated with pyroclastic flow and air fall deposits. The volcanic products found in the fluvial layers are from La Malinche volcano; these are dominantly reworked gray and reddish andesite and dacite gravels, with rare rhyolites. Overlying the volcanic and fluvial deposits is the most recent glacio-fluvial outwash debris forming the alluvial fan; this is made up of subangular to round fragments of the La Malinche andesites and dacites. During the eruption, Xalapaxco tuff cone sampled all of the underlying basement materials, incorporating sand, cobbles, and boulders as xenoliths, and ejecting some of them as bombs. For this reason it is also possible that particles observed under the SEM received their rounded and pitted character during transport as the alluvial deposits accumulated and not necessarily during explosive recycling during eruptions. The vents themselves are currently filled with slump debris from mass wasting of the steep vent walls into the pits.

A schematic history of the formation of the Xalapaxcotuff cone is as follows: Global climatic changes during the Quaternary resulted in development of major glacial episodes, affecting the high volcanic peaks in central Mexico. The last major glaciation of the summit of La Malinche occurred about 8,000 to 10,000 yr BP. During the glacial stages a deep glacial canyon was carved on the northeast flank of the volcano. Warming climate caused the glaciers to melt, leaving a deep incised canyon, Barranca Axaltzintle, at the headwater of a drainage. Alluvial and reworked glacio-fluvial materials were deposited as a triangular-shaped alluvial fan on the flank of La Malinche. On the other sides of the volcano, parallel, incised drainages developed, cutting into the pyroclastic deposits, also found below the alluvial fan. Continued volcanic activity at La Malinche resumed when rising magma ascended through the limestone basement, pierced intercalated fluvial and pyroclastic layers, and finally breached the alluvial fan to erupt on the surface. The magma encountered large volumes of water, particularly in the alluvial fan which acted as an aquifer that was fed by a large area of the volcanic edifice. Other sources of groundwater were in the limestone basement, which has high permeability and could form karstic voids; and in the overlying

intercalated fluvial and pyroclastic beds. The high water/magma ratio, estimated to be between 0.5 and 1.0 (Wohletz and Heiken, 1991), produced phreatomagmatic eruptions of moderate explosivity at shallow depths. Eruptions were short-lived, as evidenced by the lack of soils between beds. Construction of the cone was by way of base surges and fall deposits. The juvenile magma was most probably porphyritic dacite similar in composition to La Malinche lavas. After cessation of eruptive activity, the cone has been modified by erosion, producing small gullies on the sides; and by slumping of material into the craters, partially filling them.

The peculiar setting of the Xalapaxco tuff cone on the flanks of a stratovolcano is explained by the interaction of magma and groundwater under more humid climatic conditions. Under normal, drier conditions, or in a drier environment, Xalapaxco might have formed as a dacite dome. However, because of the presence of a glacio-fluvial alluvial fan, storing and channeling large quantities of water, ascending magma reacted phreatically to produce a tuff cone. It is therefore possible to at least partially attribute the formation of Xalapaxco to the peculiar configuration of hydrologic conditions that prevailed during the last glacial stage in this area.

### **Acknowledgements**

Work by M. Abrams was performed at the Jet Propulsion Laboratory/California Institute of Technology under contract to the National Aeronautics and Space Administration. Part of the expenses for this study were defrayed by a grant from CONACYT (0631-3'911 O) to Claus Siebe and by the Instituto de Geofísica, UNAM. We want to thank J. C. Komorowski and M.F. Sheridan for critical comments of an earlier version of this manuscript. Suggestions and constructive criticism by Greg Valentine and two anonymous reviewers also improved the manuscript. Work with the SEM was done at the Instituto de Geología, Universidad Nacional Autónoma de México, with the help of Margarita Reys.

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### Figure captions

1. Location map showing the Xalapaxcotuff cone on the northeastern flank of La Malinche stratovolcano, central Mexico, northeast of Puebla. The area is located in the eastern part of the Trans Mexican Volcanic Belt, an active arc related to the subduction of the Cocos Plate under the North American Plate.
2. Perspective view showing the NE slopes of La Malinche volcano, the prominent alluvial fan on which Xalapaxcotuff cone is located, and Barranca Axaltzintle. The image combines Landsat Thematic Mapper satellite image data and digital topographic data.
3. Landsat Thematic Mapper satellite image of the area around La Malinche volcano, central Mexico. The image covers an area of about 60 x 60 km, with a resolution of about 30 m. The Xalapaxcotuff cone is the small circular feature on the east flank of the volcano.
4. Drainage network map of La Malinche volcano, interpreted from Figure 3. Most of the drainages are parallel and closely spaced, forming a radial pattern around the summit. On the northeast flank, the Xalapaxcotuff cone is situated in a triangular alluvial fan with a marked absence of surface drainage channels.
5. Map of the Xalapaxcotuff cone. The map was redrawn from the 1:50,000 scale topographic quadrangle. Six of the craters are named "Hoyas" or clay pots: (1) Hoya Coates (2) Hoya Grande (3) Hoya Las Moneras (6) Hoya San Cristóbal (9) Hoya Las Saucotas (10) Hoya Los Texales. Section "A-B" is shown in Figure 10.
6. View from the summit area of Xalapaxcotuff cone towards SW with La Malinche stratovolcano (M) and alluvial fan (AF) in the background. In the foreground are older and partially filled explosion crater 4 and younger and deeper explosion crater 5.
7. Histograms showing typical distribution of grain size populations from Xalapaxco surge deposits. Samples 9317 and 9320 are from the silt-rich horizons; samples 9319 and 9321 are from lithic-rich horizons.
8. Outcrop within explosion pit Hoya Grande showing typical planar surge deposits from which samples for grain-size analyses and SEM were taken. Surges consist mostly of silt to sand sized clasts of andesite and dacite. Larger subangular blocks show impact sags (arrow) in layers which are 2-10 cm thick. Clasts of chert, limestone, and welded tuff are present. The plane parallel layering is obvious when wet.
9. SEM images taken with secondary electron imaging mode of typical particles found in Xalapaxco surge deposits (1  $\phi$  size fraction). All show rounded grains with pitted and abraded surfaces and modified edges. Note the lack of fresh fracture surfaces but the abundance of small-scale features ( $<20\mu\text{m}$ ) which suggest a low energy environment within which numerous grain-to grain collisions took place. This would be compatible with a particle-loaded environment of repeated abrasion of recycled clasts. Scale bars are 1 mm.

(A) Typical limestone clast from the Cretaceous basement, with rounded edges, pitted and sand-blasted surfaces. (B) Rounded, pitted and sand-blasted chert grain from nodules within the Cretaceous limestone. (C) Subrounded clast of volcanic glass that might be of juvenile origin; note the significant state of edge modification and surface abrasion. (D) Typical vitric sub-angular clast of weakly vesiculated La Malinche dacite showing crystals of plagioclase and hornblende.

10. Interpretative cross-section of the Xalapaxco tuff cone. The underlying basement consists of Cretaceous limestone; above arc intercalated fluvial layers and pyroclastic flow and air fall deposits from La Malinche. On top is the most recent glacio-fluvial fan debris, which provided an aquifer and a source for water, thus leading to explosive phreatomagmatic activity.

TABLE 1. Dimensions of Xalapaxco eruption craters

Crater	Diameter (m)	Depth (m)	D	D i a m e t e r / I I ! h
1	436	98		4.4
2	252	48		5.2
3	283	60		4.7
4	113	25		4.5
5	152	41		3.7
6	111	38		2.9
7	140	35		4.0
8	154	40		3.8
9	174	45		3.9
10	200	27		7.4

TABLE 2. Whole rock chemical analyses of Xalapaxco tuff cone xenoliths

Sample #	9101 rhyo*	9103 Chert	9104 Dacite
SiO <sub>2</sub>	70.70	60.00	65.70
TiO <sub>2</sub>	0 . 2 0	0.43	0.63
Al <sub>2</sub> O <sub>3</sub>	10.4s	9.8	15.28
Fe <sub>2</sub> O <sub>3</sub>	1.62	3.32	4.32
MnO	0.04	0.06	0.07
MgO	0.31	1.80	2.62
CaO	4.94	12.38	4.84
Na <sub>2</sub> O	2.85	2.64	4.25
K <sub>2</sub> O	3.57	1.45	2 . 1 0
P <sub>2</sub> O <sub>5</sub>	0.12	(.) . 13	(.) . 17
LOI	3.89 .....	7.79	(.) . 34
TOTAL (%)	98.69	99.78	100.32
La**	30.0	14.0	17.0
Ce	50.0	26.0	32.()
Nd	17.0	14.0	15.0
Sm	2.8	2.8	3.4
Eu	0.7	1.0	1.1
Tb	<1.0	<1.0	<1.0
Tm	<2.0	<2.0	<2.0
Yb	2.0	<1.0	1.0
Lu	0.3	<().2	<0.2
Sc	1.9	7.1	10.0
Th	18.0	?) . ()	4.2
u	3.()	1.0	1.0
Y	20.0	10.0	16.0
BaO <sup>+</sup>	0.058	() . 040	0.053
Cr <sub>2</sub> O <sub>3</sub>	0.07	0.05	0.02
s	0.02	0.03	0.02

\* Densely welded rhyolitic ash flow tuff

\*\* ppm

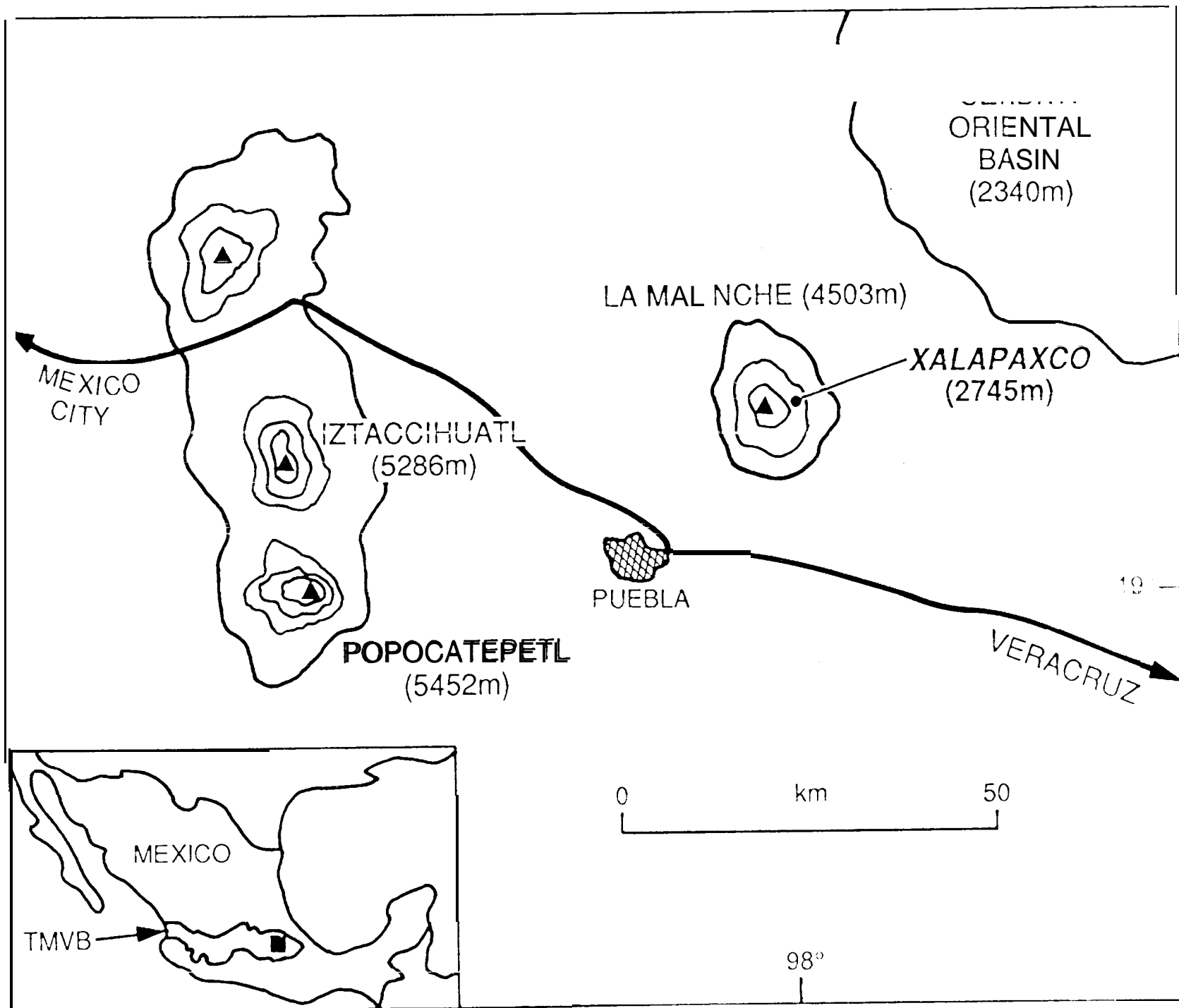
+ %

TABLE 3. Modal analyses (vol. %) of Xalapaxco tuff cone xenoliths (>500 points counted)

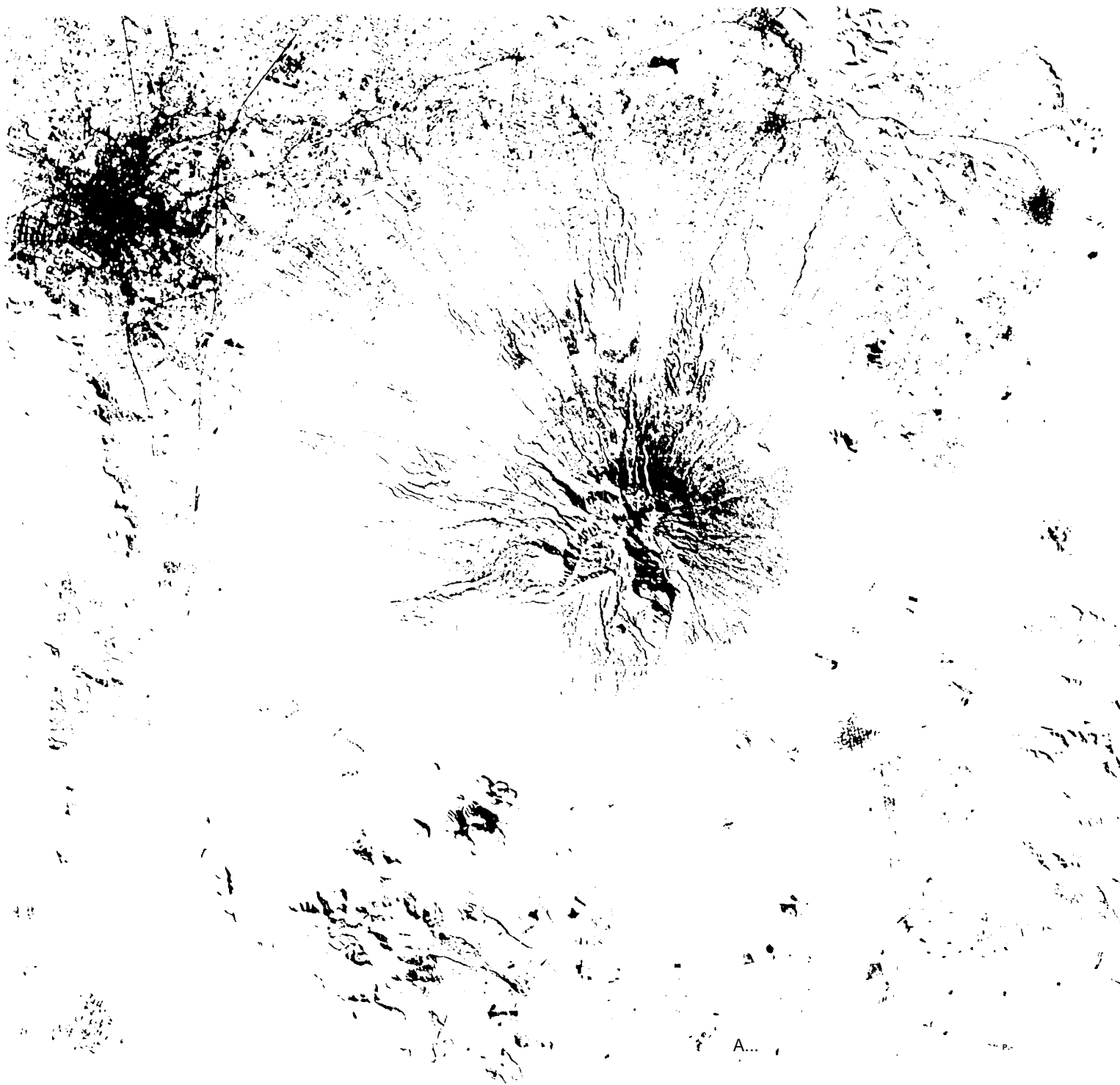
Sample #	9101 rhyo"	9103 Chert	9104 Dacite
Plagioclase	7.8	22.6	21.4
Hornblende	0.0	10.6	11.0
Biotite	0.6	0.2	3.8
Magnetite	0.4	3.0	1.4
Pumice	8.2	0.0	0.0
Matrix	83.0	63.6	62.4
TOTAL	100.0	100.0	100.0

Deniscly welded rhyolitic ash flow tuff

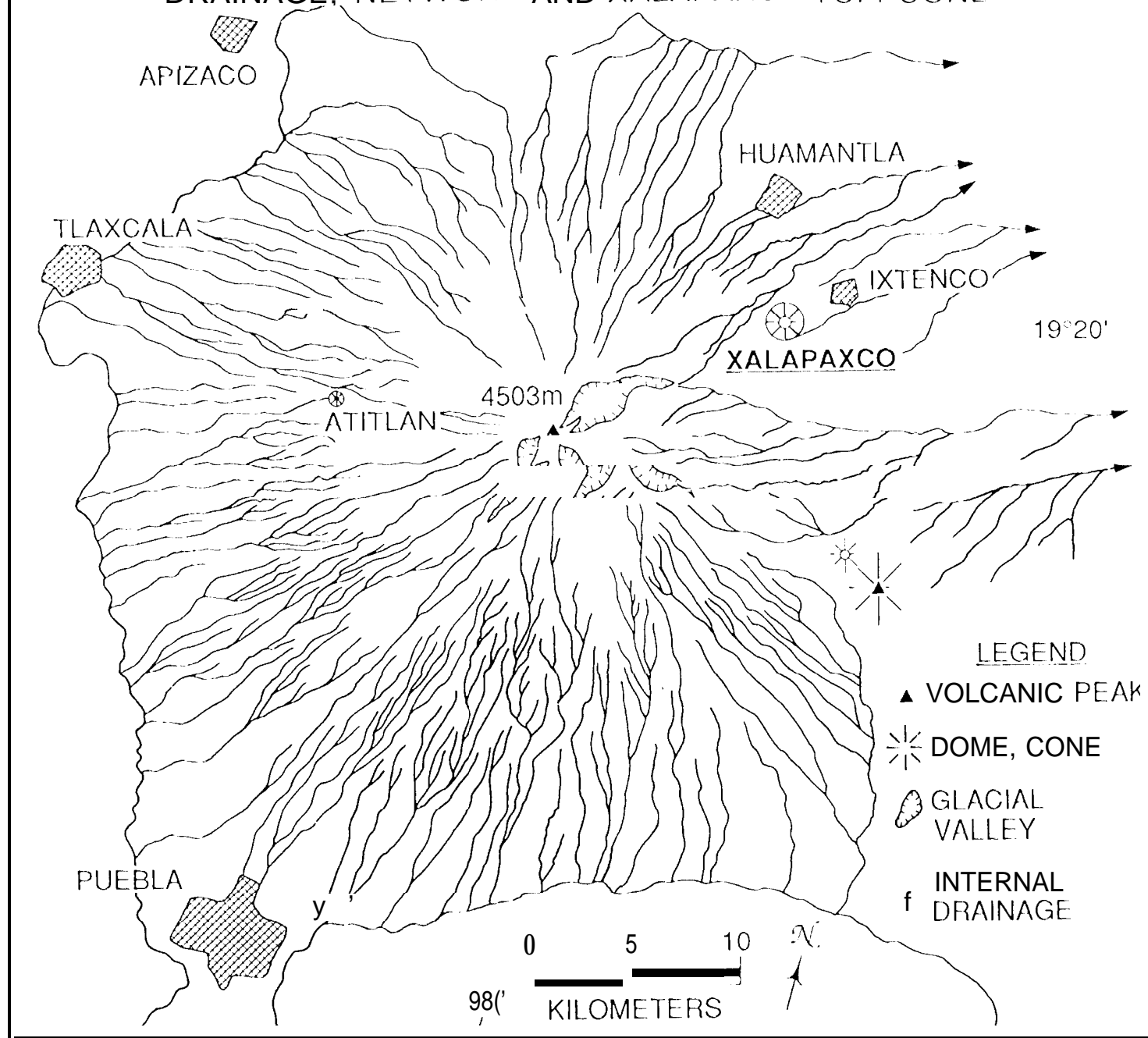


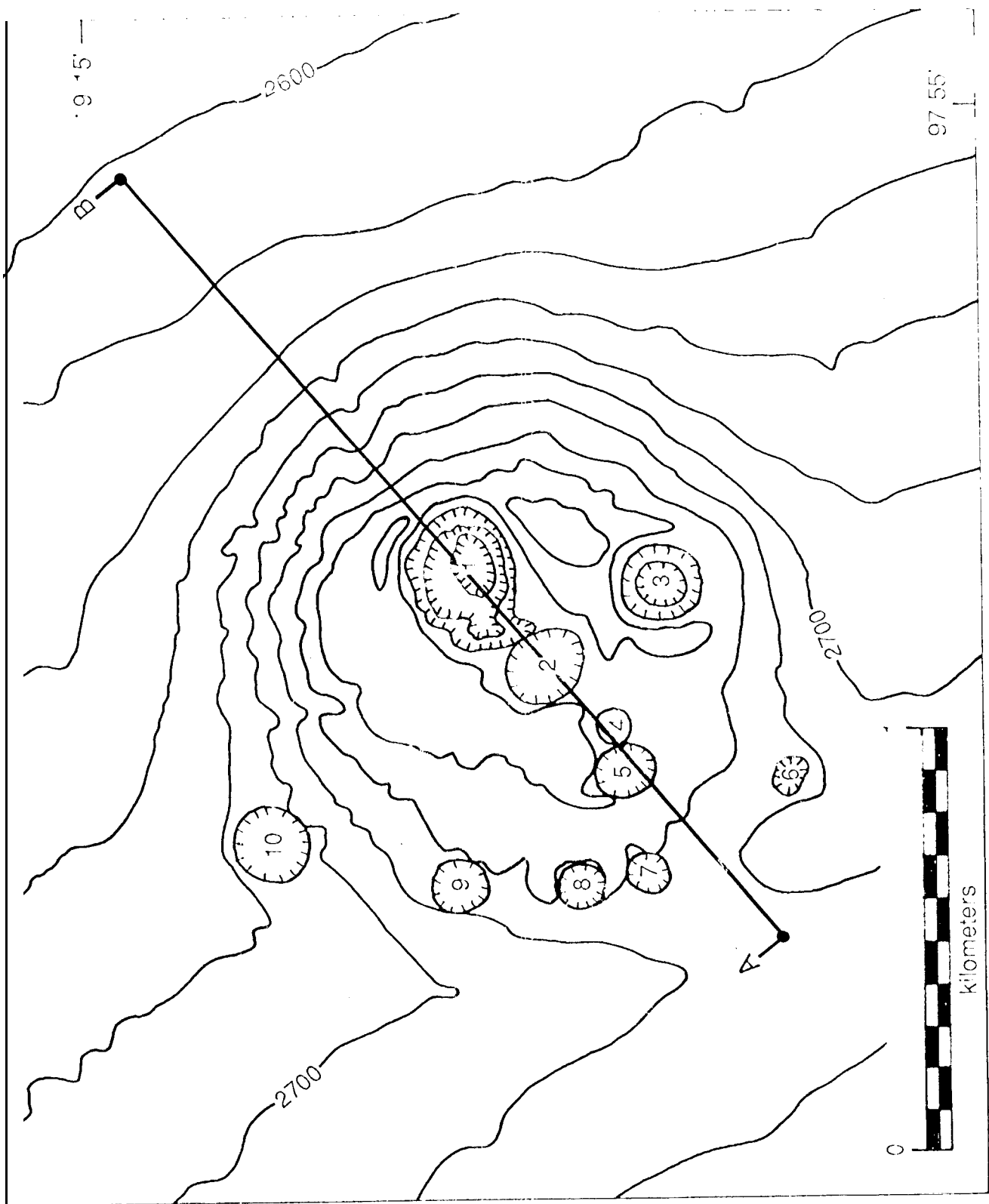






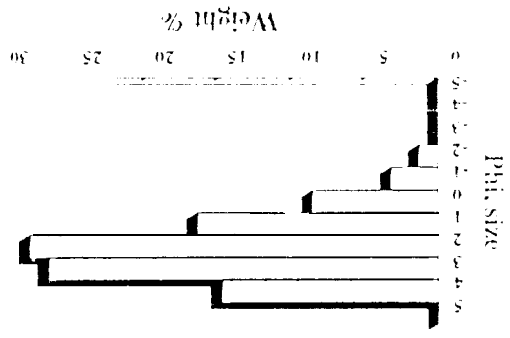
LA MALINCHE VOLCANO, MEXICO  
DRAINAGE: NETWORK AND XALAPAXCO TUFF CONE



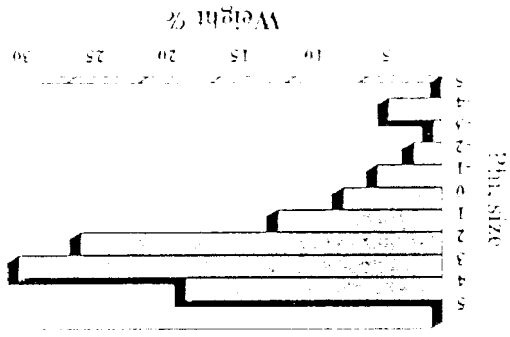


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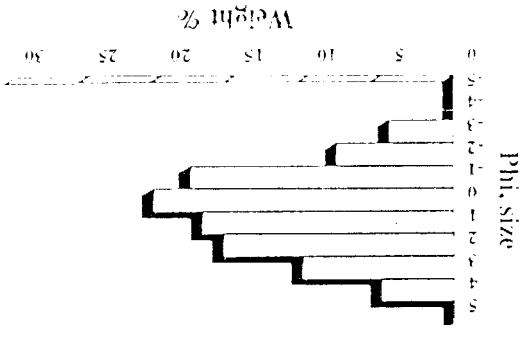




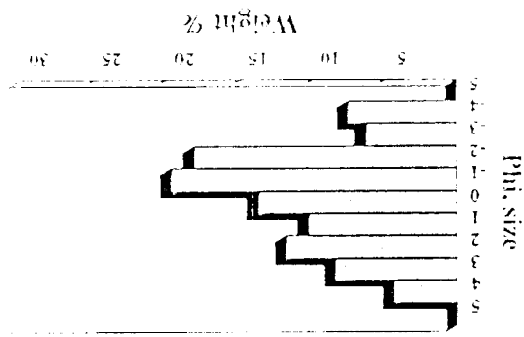
Xalapaxco 9320



Xalapaxco 9317



Xalapaxco 9321



Xalapaxco 9319





